Sub-picosecond measurements of photoinjector electron beam properties

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Outline

- *Introduction to DUVFEL*
- *Thermal emittance and RF gun studies*
  - Beam based studies of applied photoinjector fields
  - Experimental/instrumentation issues
  - Thermal emittance scaling measurement
- *Microbunching and femtosecond transverse dynamics*
  - Subpicosecond instrumentation
  - Compressed beam measurements and microbunching.
  - Slice emittance measurement and observation of laminar/cross-over trajectories

DUVFEL Program

Designed to produce fully coherent radiation using the high-gain harmonic generation process.

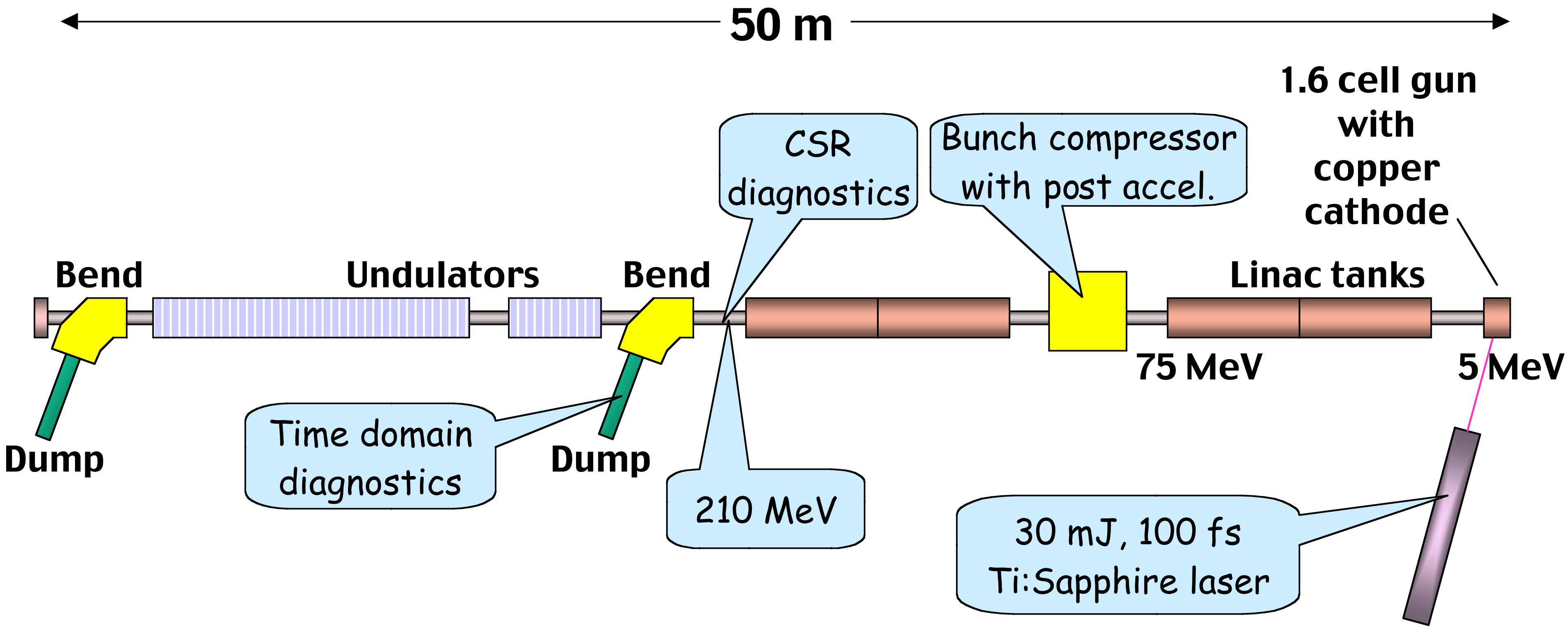
Facility consists of

- Titanium:Sapphire seed laser
- RF photocathode and 210 MeV linac
- Bunch compressor for kA class beam.
- 10m NISUS undulator: 3.9 cm period, K=1.

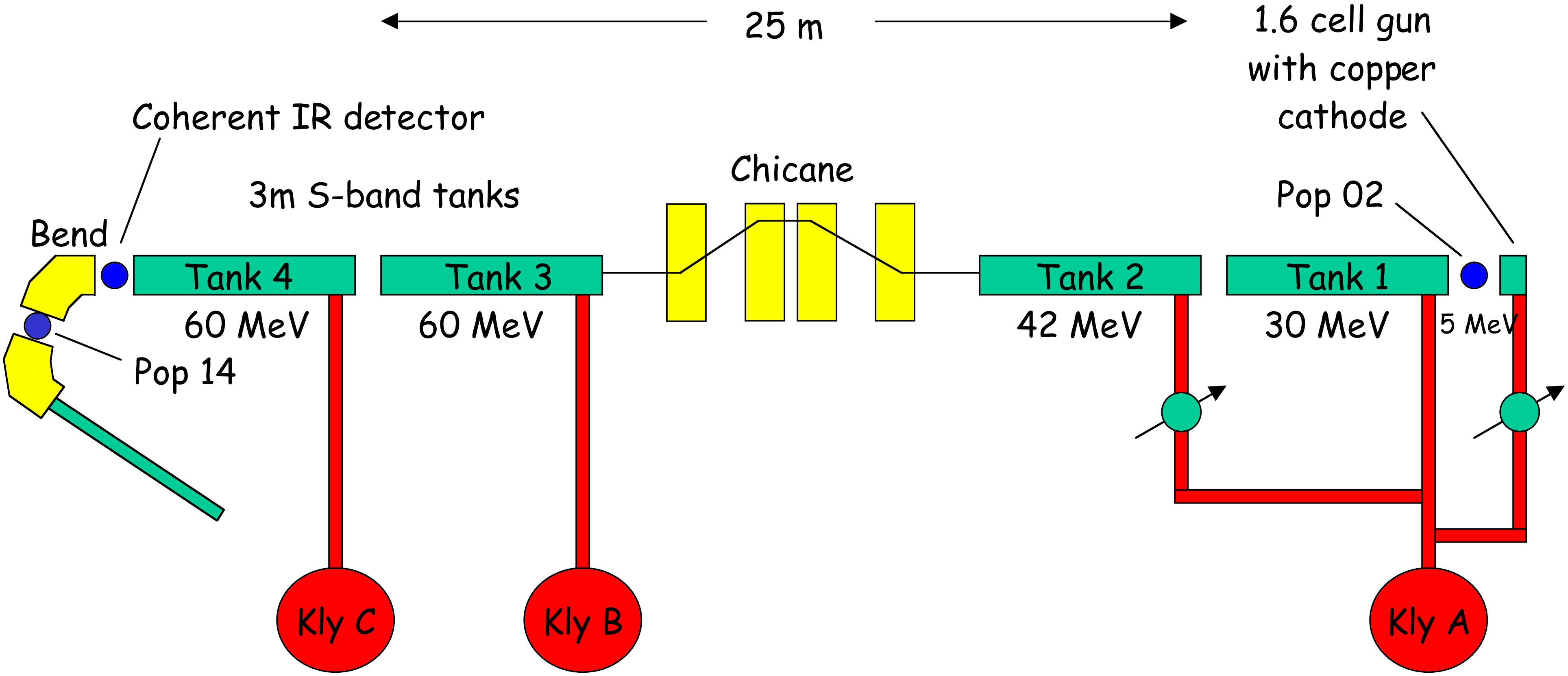
Status

- Linac fully commissioned
- Now commissioning SASE FEL experiments at 400 nm.
- Move rapidly to 200 nm in fundamental, 67 nm in 3rd harmonic.
- Seed with conventional laser (high gain harmonic generation – HGHG).
- Future: Upgrade energy to 310 MeV, reach 30 nm wavelength

DUVFEL Facility



DUVFEL Accelerator



45 MW Thompson Klystrons

30 mJ, 100 fs Ti:Sapphire laser

DUVFEL Photoinjector

1.6 cell BNL/SLAC/UCLA Gun IV

Cathode material	Copper
Max energy	5.1 MeV
Loaded Q	7100
Unloaded Q	13500
RF pulse length	2.5 us
Quantum efficiency	~2e-5
Vacuum	~8e-9 torr
Phase jitter	< 1ps

Titanium:Sapphire Laser

IR laser energy	30 mJ
UV laser energy	2 mJ
Laser pulse length	2-4 ps FWHM

Normal incidence in-vacuum mirrors

Laser pulse length in IR is adjustable from 100 fs to 10 ps. UV output limited to narrow pulse length range due to BBO harmonic crystals.

Photoinjector Issues

Lack of agreement between theory/simulation and experiment

> "In most laboratories…there is considerable disagreement between the experimental data and the predictions of PARMELA and the semi-analytic tools. We note that PARMELA and the semi-analytic approach are in good agreement with each other. One should ask the following questions:
>
> (i) Are there some subtleties in the experimental setup that have prevented the beams from achieving the conditions used in the simulations?
>
> (ii) Is there some fundamental physics of the beam dynamics near the cathode that is not well modeled by our codes?"
>
> -excerpted from the *4th Report of the Technical Advisory Committee* to the Linac Coherent Light Source project, January, 2001.

Solution is to reduce complexity of beam dynamics, achieve agreement between theory and experiment, then add complexity (more charge, longer bunches…collective effects).

Envelope equation

$$\sigma_x{}^{?} = \underbrace{\frac{\gamma'}{\gamma^3\beta^2}\sigma_x{}'}_{\text{Acceleration}} - \underbrace{\frac{\sigma_x}{2\gamma\beta^2 mc^2}\left(\overline{E_z}{}'\sin\phi + \frac{\omega_{rf}\beta}{c}E_z\cos\phi + B_z{}^2\right)}_{\text{Applied E and B fields}} + \underbrace{\frac{Q}{\gamma^3\beta^2\sigma_x\sigma_z}h_x}_{\text{Space charge}} + \underbrace{\frac{\varepsilon_{xN}{}^2}{\gamma^2\sigma_x{}^3}}_{\text{Emittance}}$$

Different time slices of beam experience different forces due to RF sinusoid and space charge.

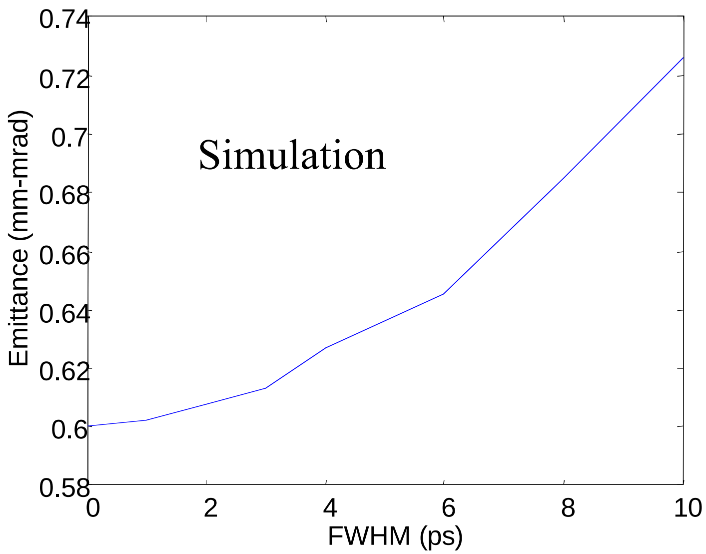
Emittance compensation is the process of untwisting the time slices so that they align.

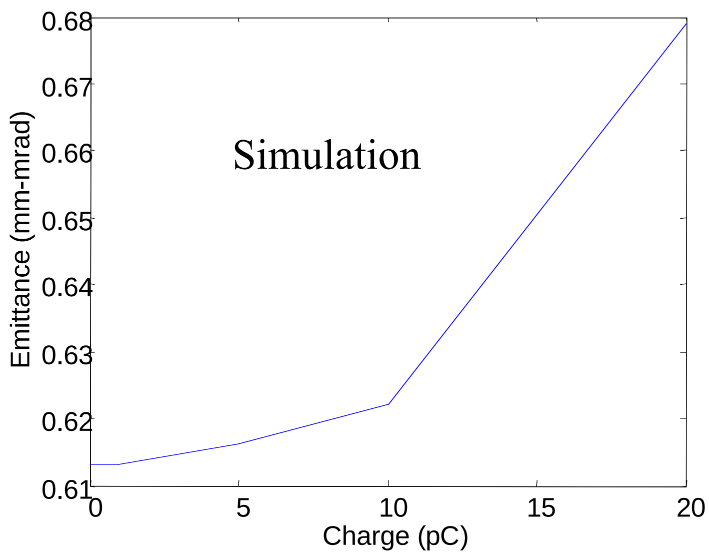
Nonlinear fields cause irreversible emittance growth (not time correlations).

We avoid these effects by working with short, low charge beams transported over short distances.

Projected emittance vs charge and FWHM

Use HOMDYN simulations to estimate limits on maximum bunch length and charge. Choose working parameters of 2 pC, 2 ps FWHM.



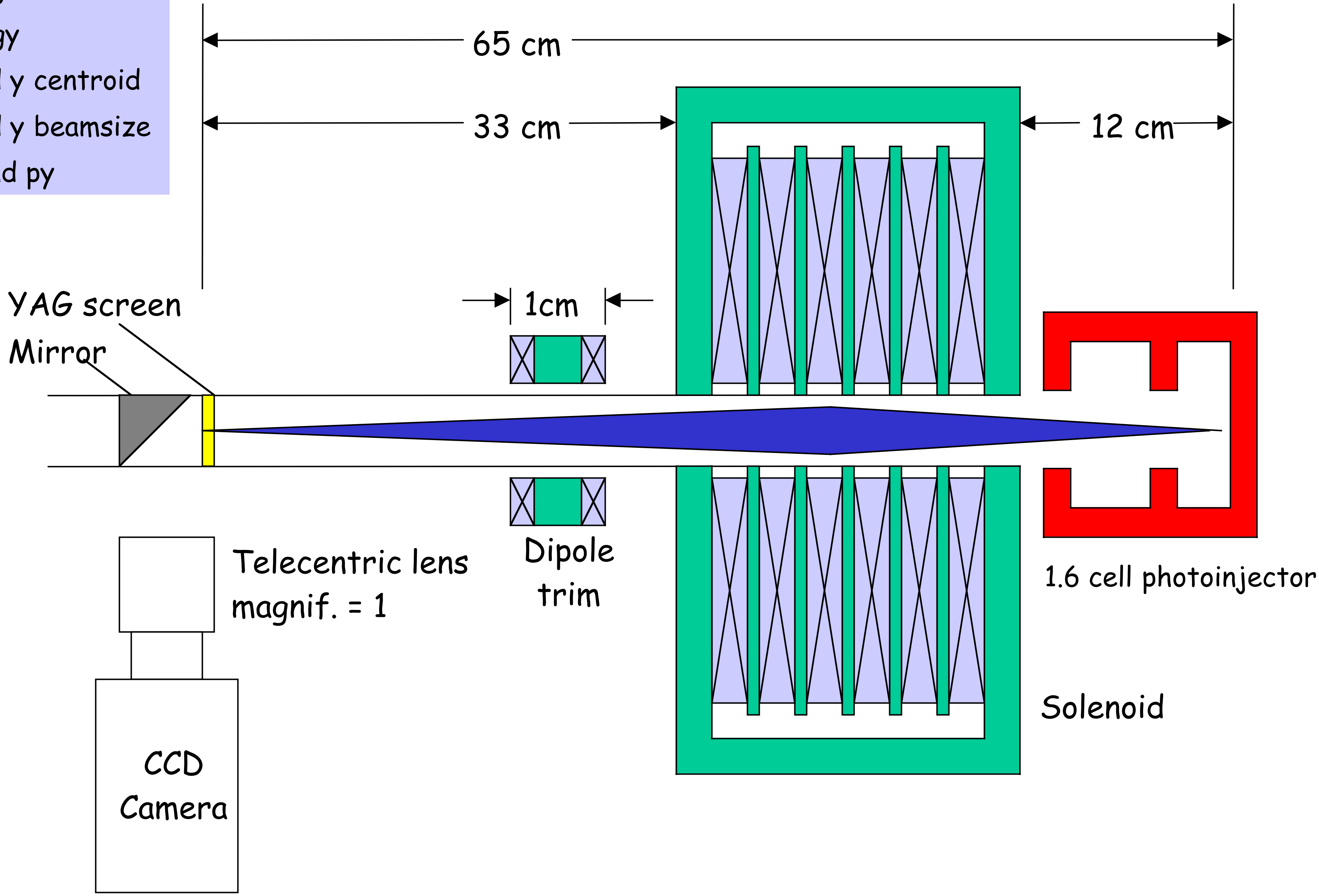


Charge 2 pC
Energy 3.7 MeV
Laser spot 0.5 mm RMS

FWHM 3 ps
Energy 3.7 MeV
Laser spot 0.5 mm RMS

Solenoid Scan Layout

Can measure
- charge
- energy
- x and y centroid
- x and y beamsize
- px and py



Solenoid Scan Equations

Usual transport equation is

$$\sigma_1 = R\sigma_0 R^T$$

where σ and R are 4x4 matrices.

Desire to decouple x and y so that

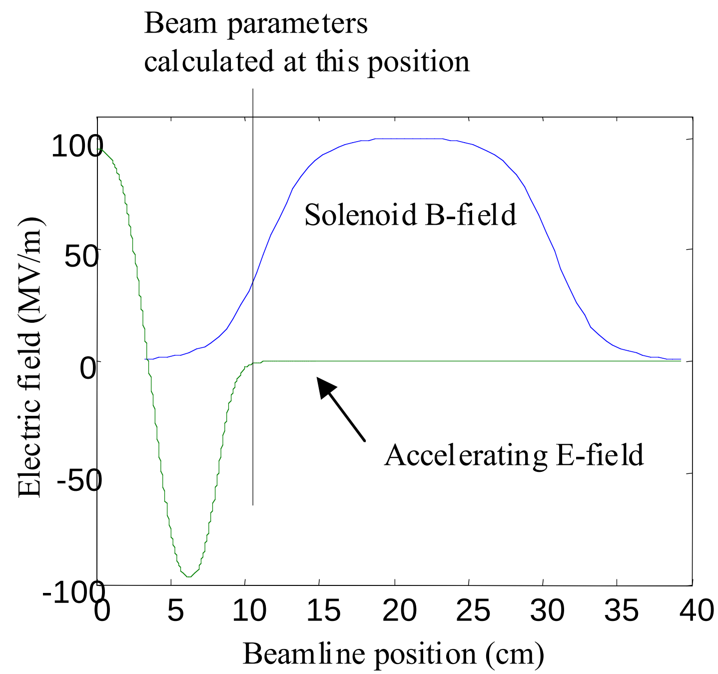
$$\langle x_1^2 \rangle = R_{11}^2 \langle x_0^2 \rangle + 2R_{11}R_{12}\langle x_0 x_0' \rangle + R_{12}^2 \langle x_0'^2 \rangle$$

Multiply by rotation matrix *T* to decouple *R*-matrix and "unrotate" beam projections.

$$R \blacklozenge TR$$
$$\sigma \blacklozenge T\sigma$$

$$T = \begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & \cos\theta & 0 & \sin\theta \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

$$\theta = \frac{eBL}{2\gamma mc^2} = \arctan\frac{R_{31}}{R_{11}}$$

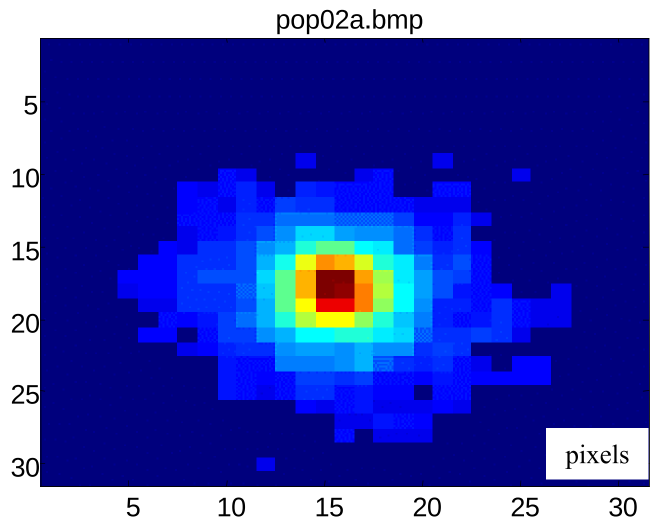


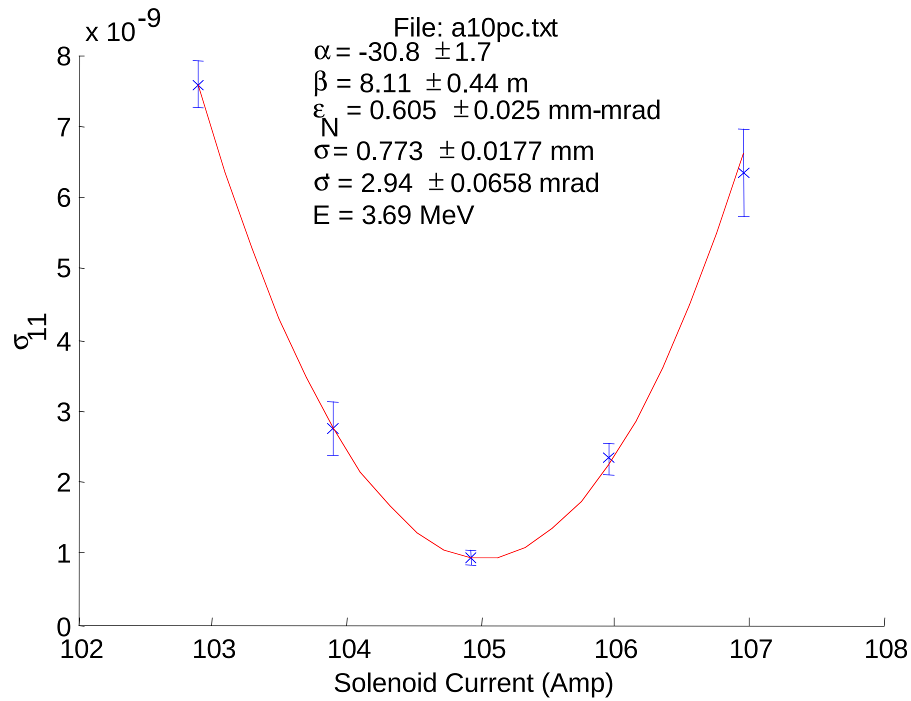
Break solenoid into 40 slices for accurate field profile.

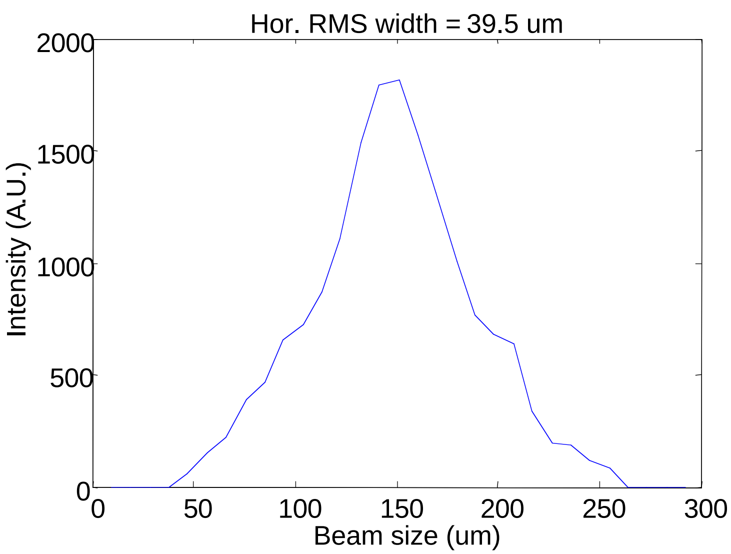
Build transport matrix by summing slices.

Use MAD and Matlab.

Low Energy Beam Measurements







Video processing

•3x3 median filter applied.

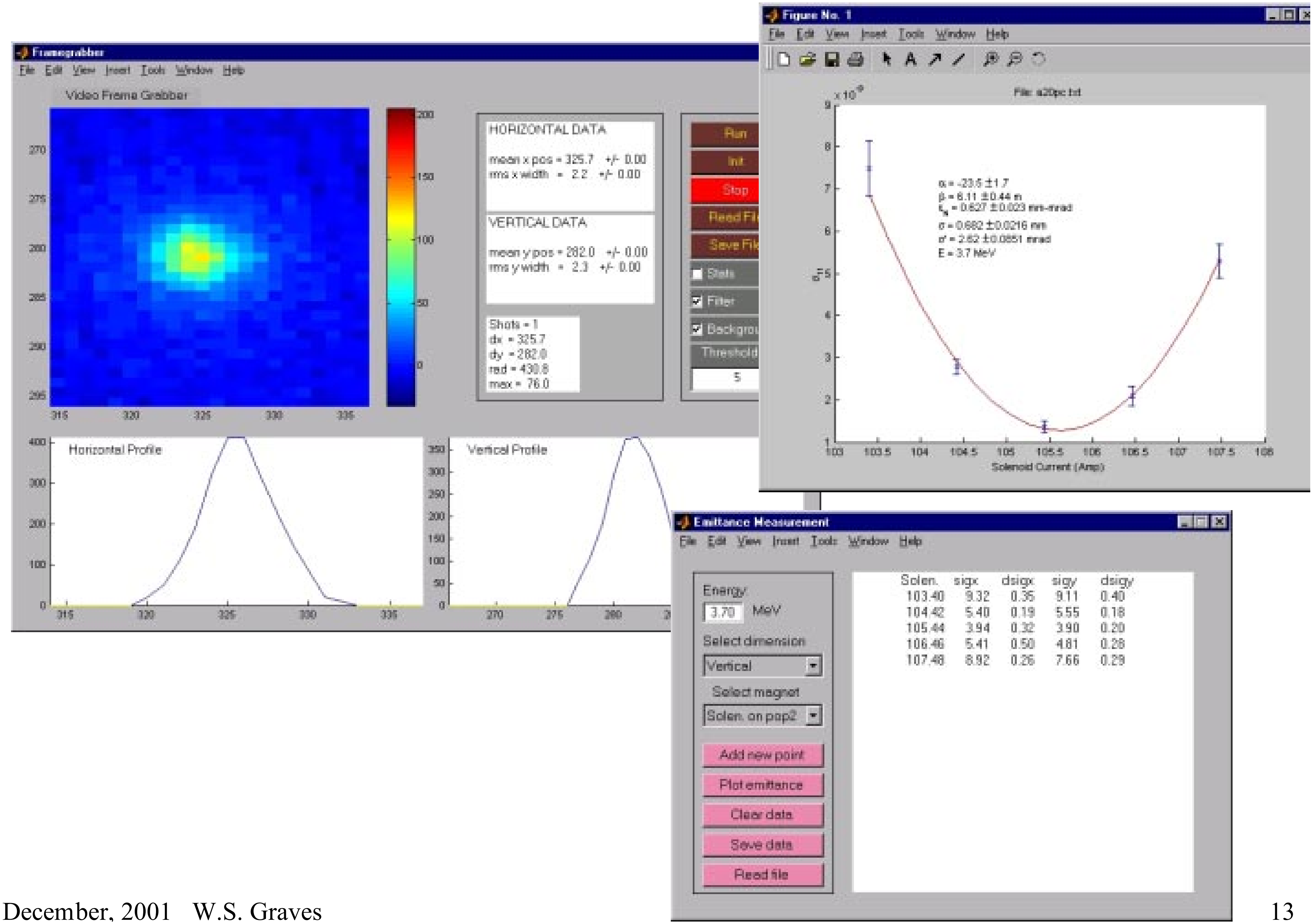
•Dark current image subtracted.

•Pixels < 10% peak are zeroed.

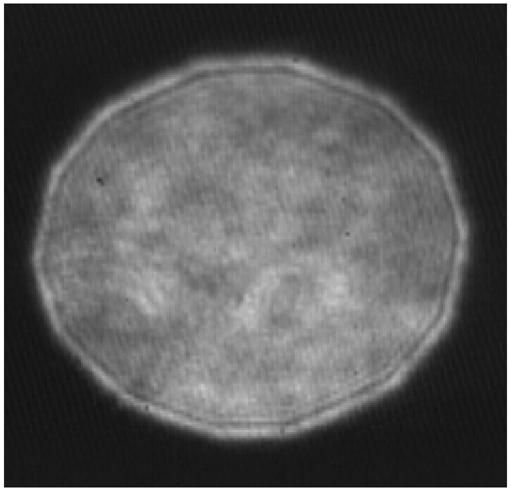
Error estimates

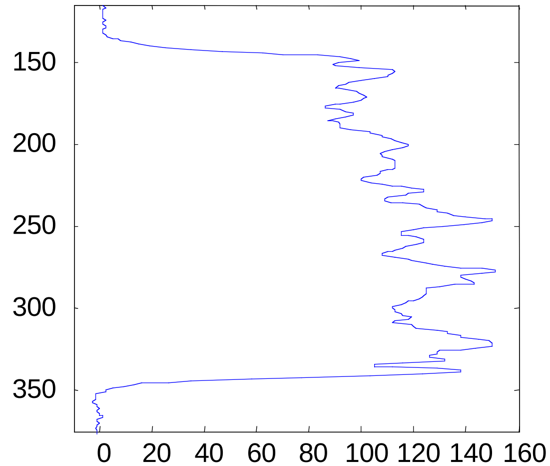
Monte Carlo method using measured beam size jitter.

User Interface



Laser spatial and time profiles

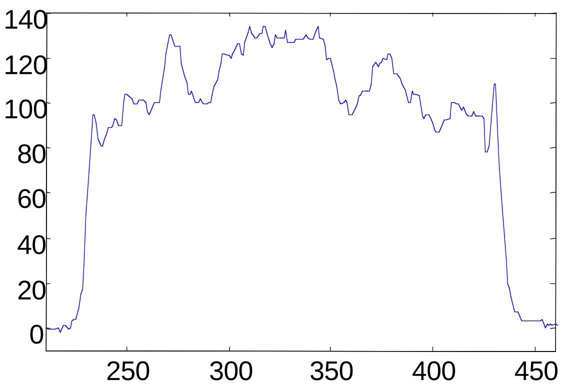




Vertical lineout

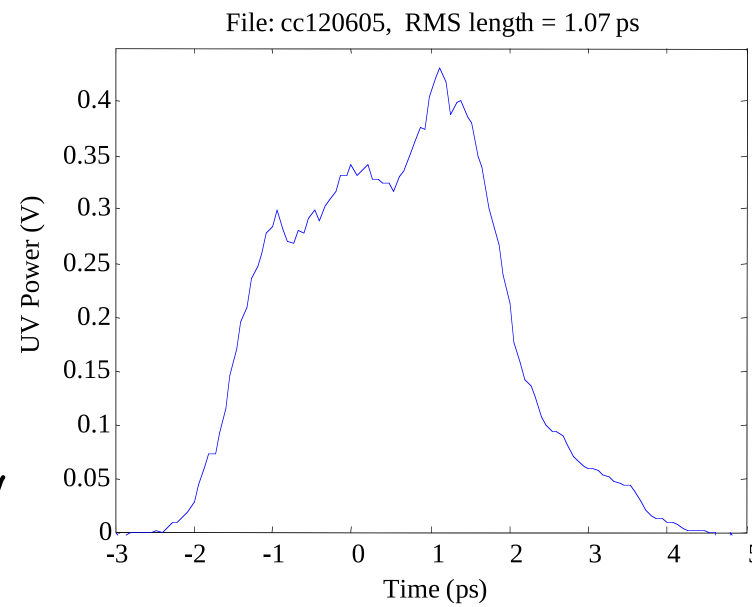
UV light is spatially filtered and apertured.

Transport calculations depend only on 2nd moments, not on spatial shape.



Horizontal lineout

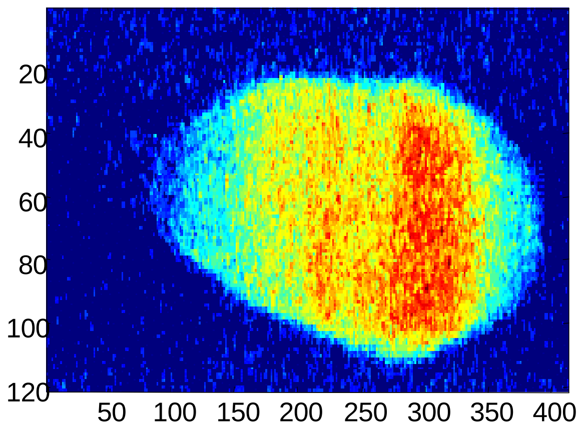
Cross-correlation measurement of UV time profile.



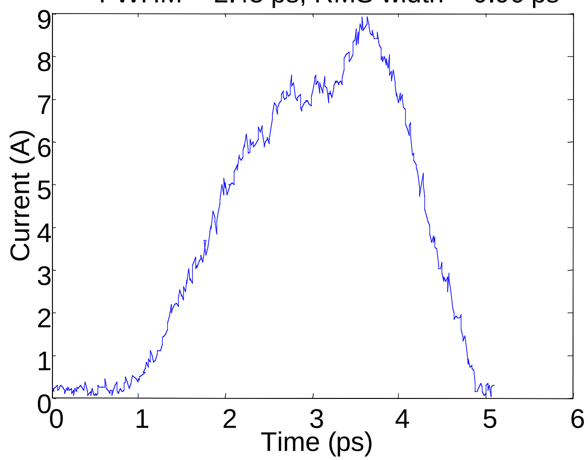
RF zero phasing electron bunch length measurement

Energy = 75 MeV, Charge = 20 pC, Tank 4 energy gain = 11 MeV

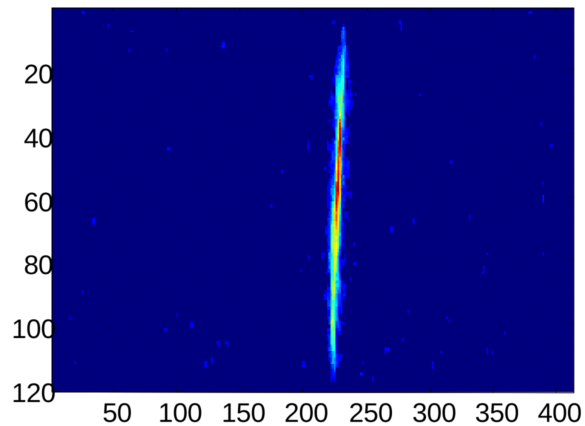
RF phase = -90 degrees



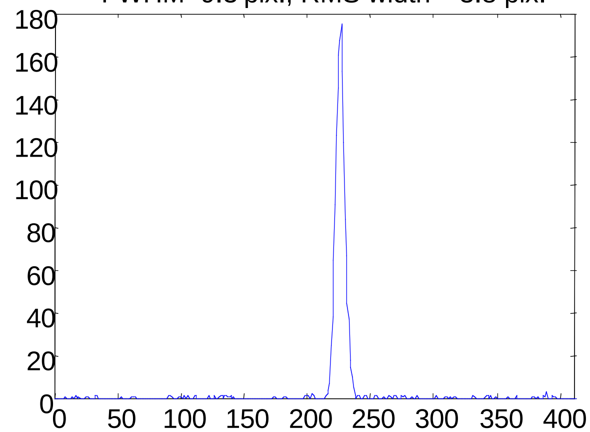
FWHM = 2.45 ps, RMS width = 0.90 ps



RF is off

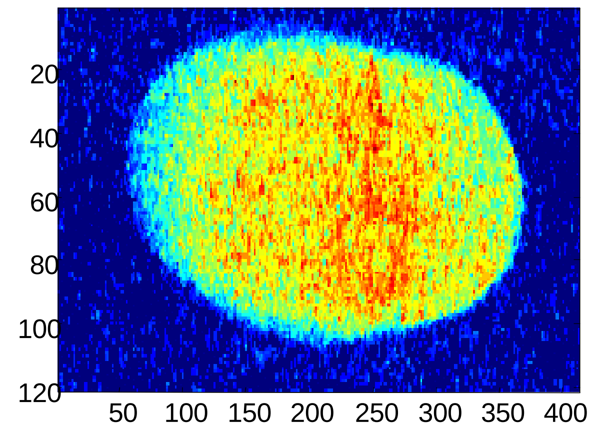


FWHM=9.3 pix., RMS width = 3.8 pix.

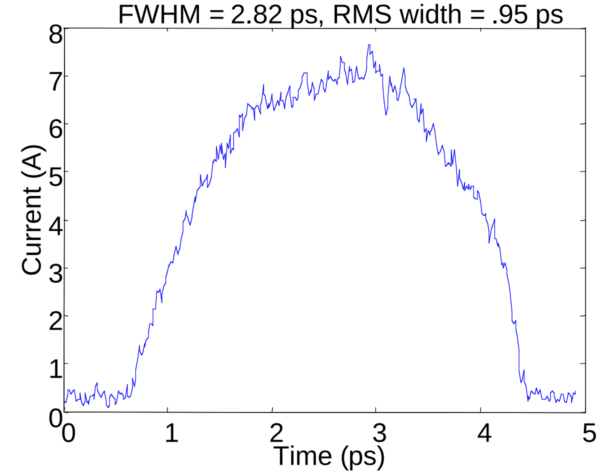


RMS energy spread = .01%

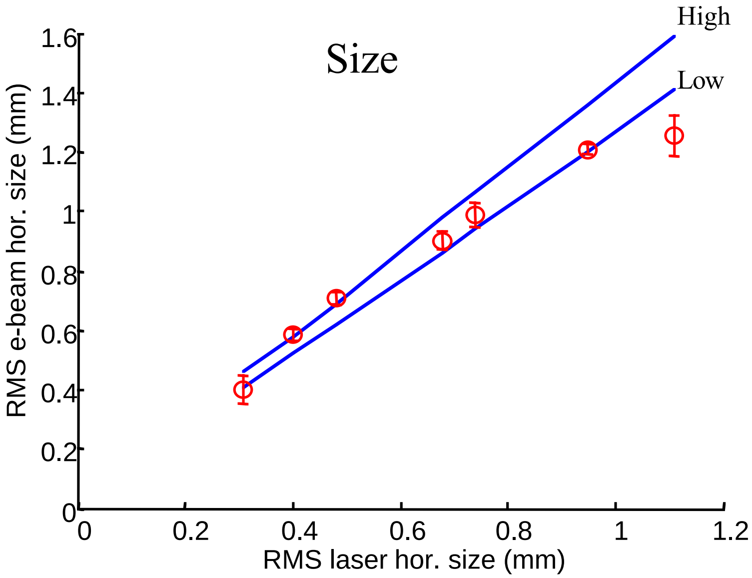
RF phase = +90 degrees



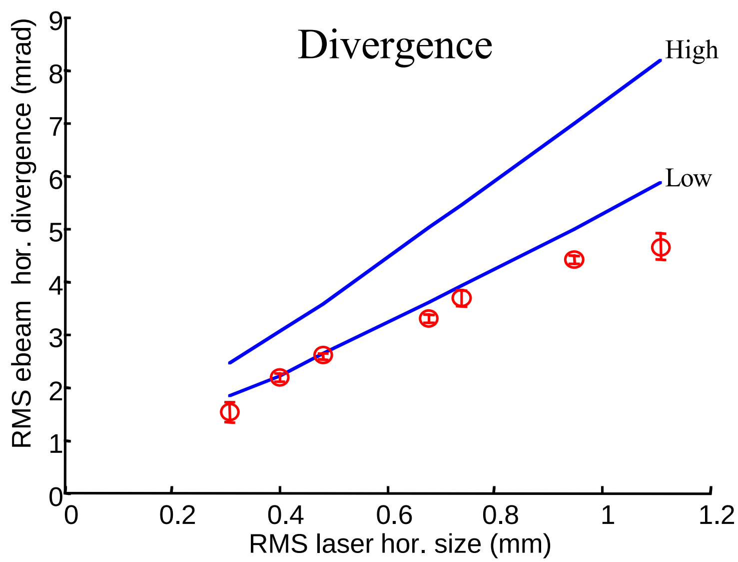
FWHM = 2.82 ps, RMS width = .95 ps



Beam size and divergence vs laser spot size



$$\sigma_{x1}[mm] = 0.12 + 1.1\sigma_{x0}[mm]$$



$$\sigma_x'[mrad] = 0.9 + 3.5\sigma_{x0}[mm]$$

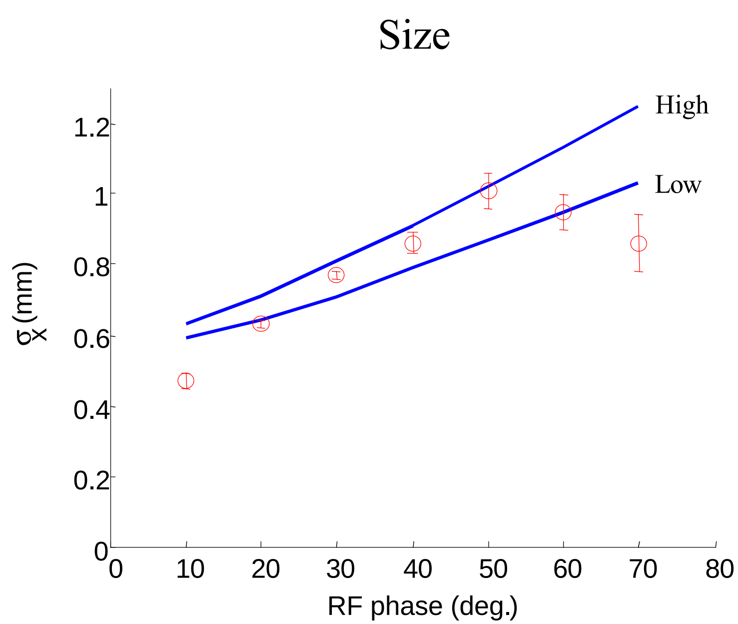
Error bars are measured data.

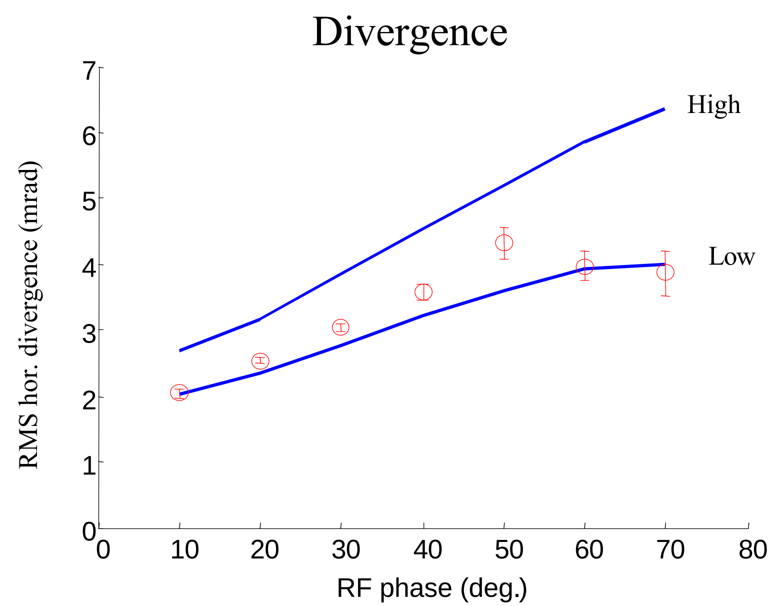
Blue lines are from HOMDYN simulation using RF fields from SUPERFISH model and measured solenoid B-field.

Upper blue line has 1/2 cell field 10% higher than full cell.

Lower blue line has 1/2 cell field 10% lower than full cell.

Beam size and divergence vs RF phase





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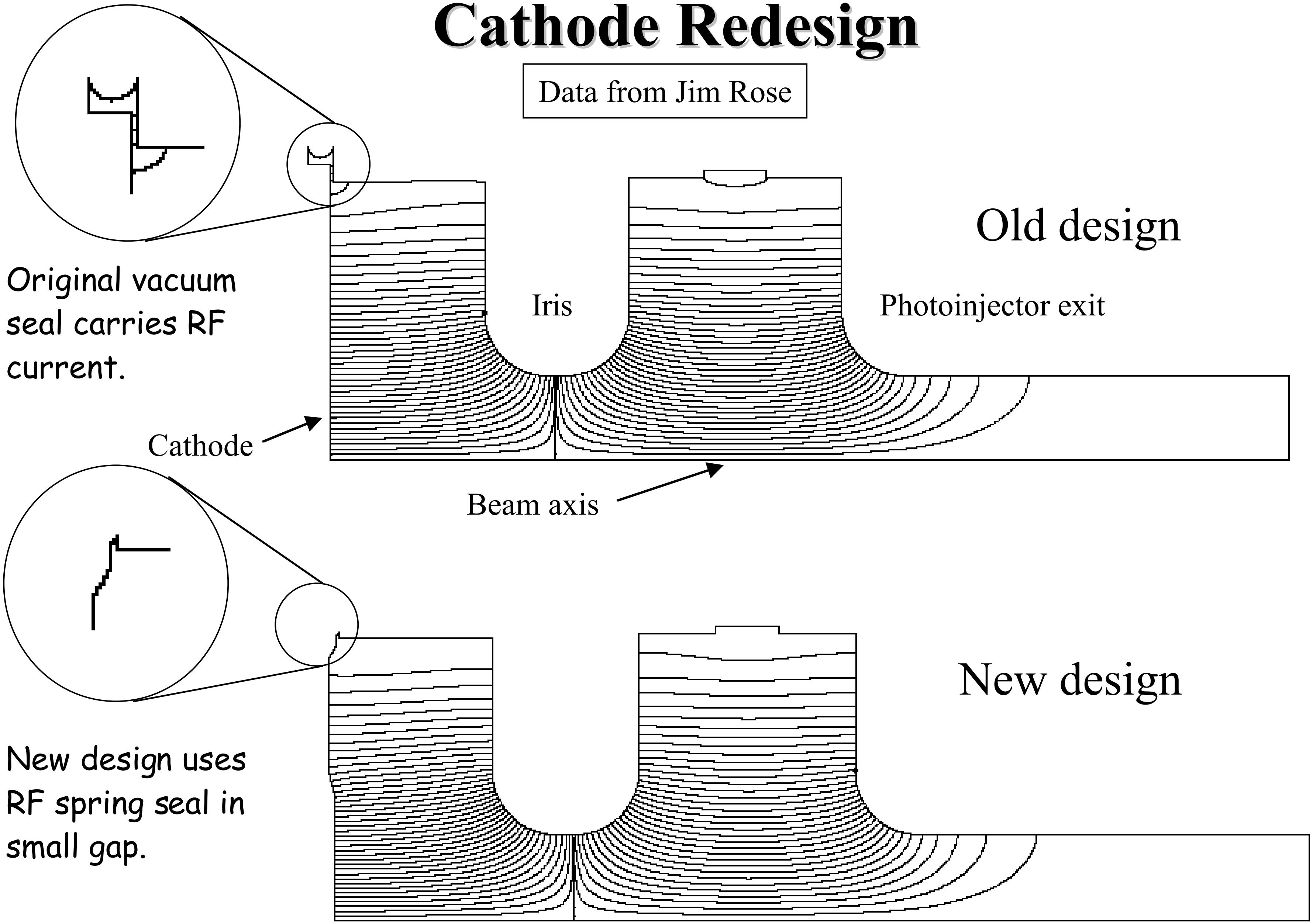
Lower line has 1/2 cell field 10% lower than full cell.

Cathode Redesign

Data from Jim Rose



Thermal Emittance

(1) $$\varepsilon_{xN} = \gamma\beta\sqrt{\langle x^2\rangle\langle x'^2\rangle} = \gamma\beta\sigma_x\sigma_{x'}$$

Use Lawson's expression for the RMS width of the momentum distribution of a thermalized beam

$$\sigma_{x'} = \sqrt{\frac{E_k}{mc^2}}$$

(2) $$?\quad \varepsilon_{\mathrm{N}} = \sigma_x\sqrt{\frac{E_k}{mc^2}}$$

(3) $$E_k = h\upsilon - \Phi_{Cu} + \alpha\sqrt{\beta_{rf}E_{rf}\sin\theta_{rf}},$$

$$\alpha = \sqrt{\frac{e}{4\pi\varepsilon_0}},\quad h\upsilon = 4.67\ \mathrm{eV}, \Phi_{Cu} = 4.59\ \mathrm{eV},$$

$E_{rf} = 95\mathrm{MV/m}$ and $\sin\theta_{rf}$ are the RF amplitude and phase, and β_{rf} is the field enhancement factor.

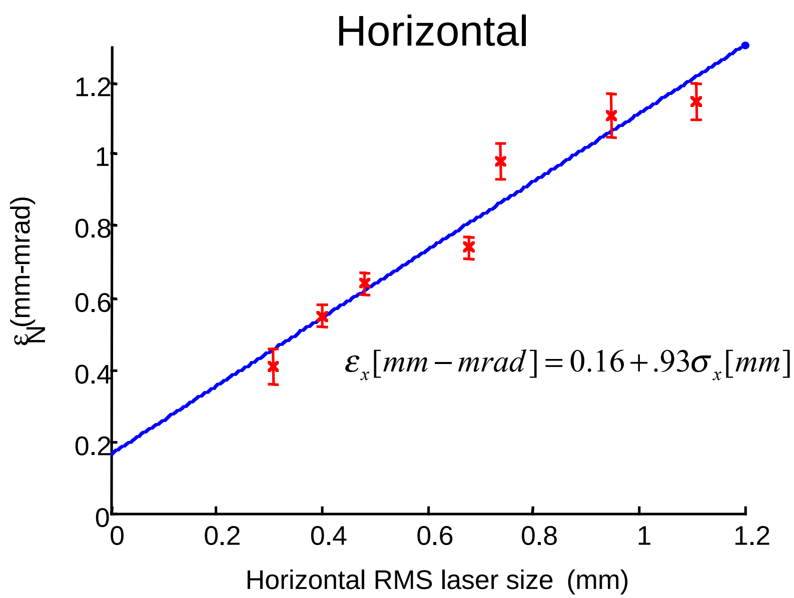
Field enhancement factor: β_{rf}

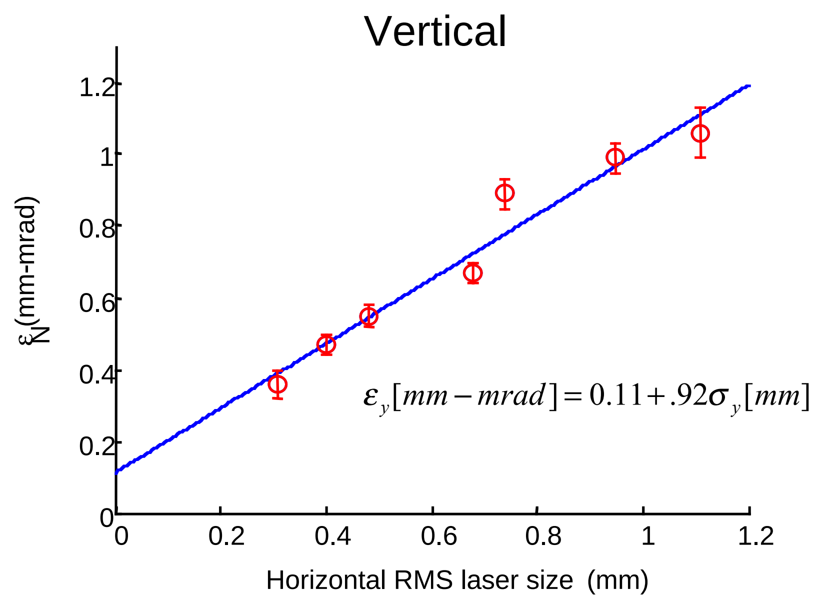
β_{rf} accounts for field variation at the cathode surface due to roughness, impurities, grain boundaries, etc.

Estimate $3 < \beta_{rf} < 10$ for a highly polished ($\lambda/2$), clean surface.

Previous theory did not account for $\beta_{rf} > 1$, resulting in underestimates of the limiting thermal emittance.

Emittance vs laser size





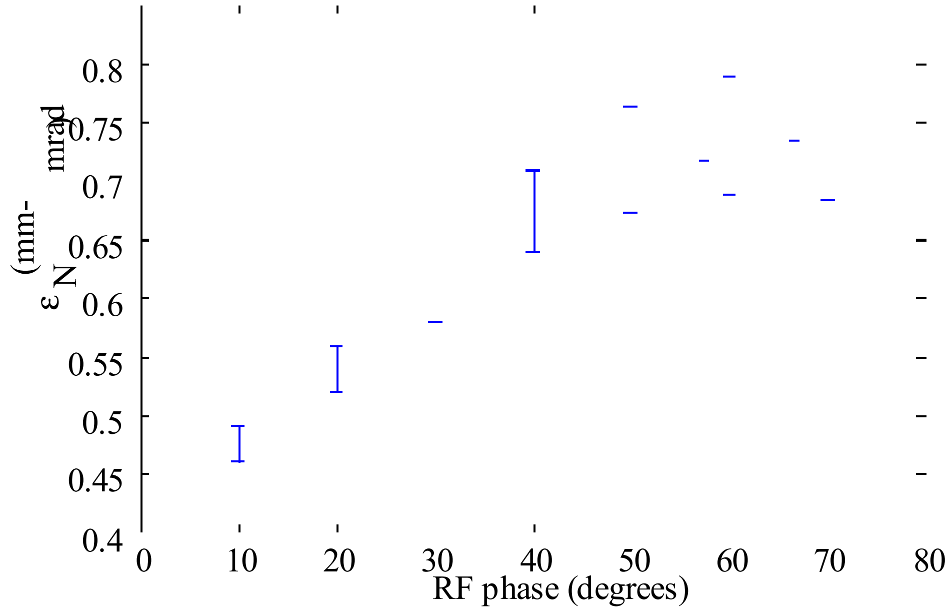
Emittance shows expected linear dependence on spot size.

Small asymmetry is always present.

Average kinetic energy $E_k = mc^2\left(\frac{d\varepsilon_N}{d\sigma_x}\right)^2 = \mathbf{0.43\ eV}$

FWHM	2.6 ps
Charge	2.0 pC
Gradient	85 MV/m
RF phase	30 degrees

Emittance vs RF phase



$$E_k = h\upsilon - \Phi_{Cu} + \alpha\sqrt{\beta_{rf} E_{rf} \sin\theta_{rf}}\,,$$

$$\alpha = \sqrt{\frac{e}{4\pi\varepsilon_0}}$$

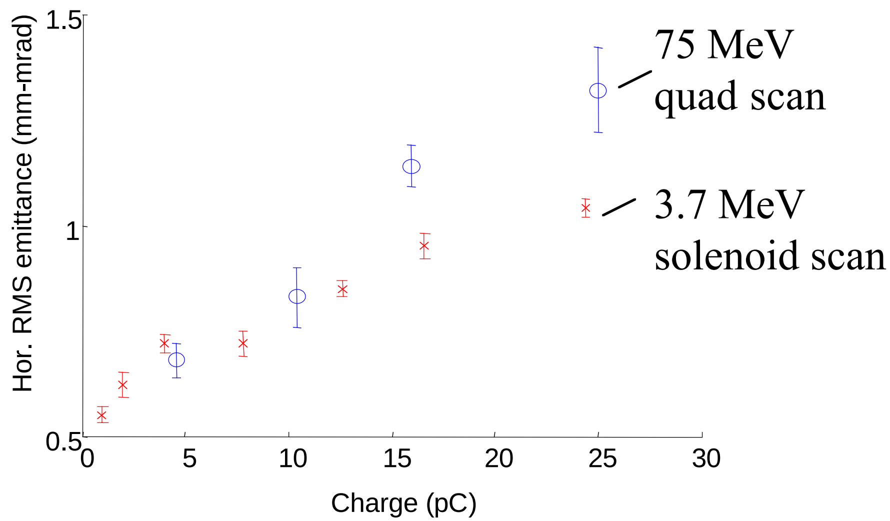
$$\varepsilon_{\mathrm{N}} = \sigma_x \sqrt{\frac{E_k}{mc^2}}$$

Error bars are measured data points.

Curve is nonlinear least squares fit with _rf and _cu as parameters: _rf **= 3.10 +/- 0.49** and _cu **= 4.73 +/- 0.04 eV**.

The fit provides a second estimate of the electron kinetic energy $\boldsymbol{E_k}$ **= 0.40 eV**, in close agreement with the estimate from the radial dependence of emittance.

Emittance vs charge



$$\varepsilon_x[mm - mrad] = 0.63 + .03Q[pC] \text{ at } 3.7 \text{ MeV}$$

$$\varepsilon_x[mm - mrad] = 0.53 + .03Q[pC] \text{ at } 75 \text{ MeV}$$

Note solenoid scan is not valid above a few pC.

Summary of laser/RF gun studies

- Measured beam dynamics show good agreement between theory and experiment in the low charge, short bunch limit after improvements to the experiments.
- First measurements of thermal emittance are in good agreement with theory.
- Attention to experimental detail is important!
- Beam-based method of characterizing photoinjector fields can be widely used.

What's next?

Shape spatial and time profiles of laser.

Analysis of slice dynamics.

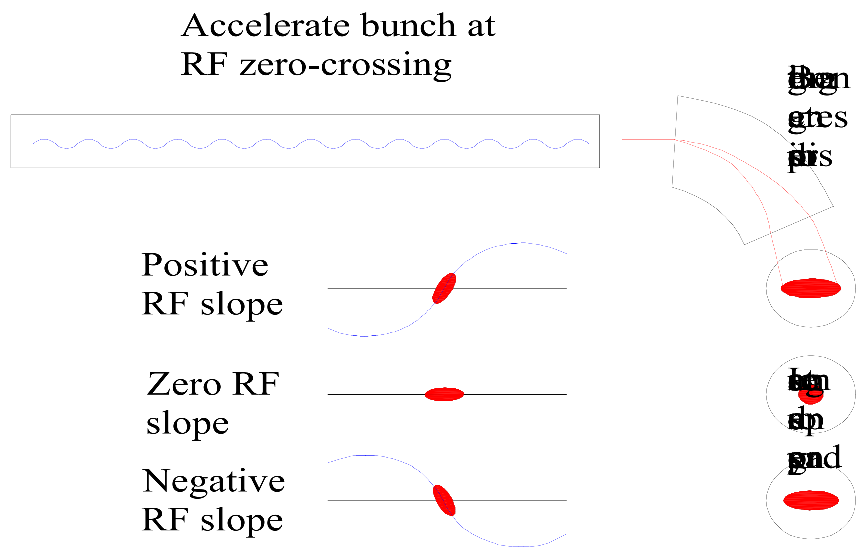
Experimental studies of emittance compensation at high charge.

Detailed compression studies.

Microbunching and femtosecond transverse dynamics

- Subpicosecond instrumentation
- Compressed beam measurements and microbunching.
- Slice emittance measurement.
- Observation of laminar/cross-over trajectories

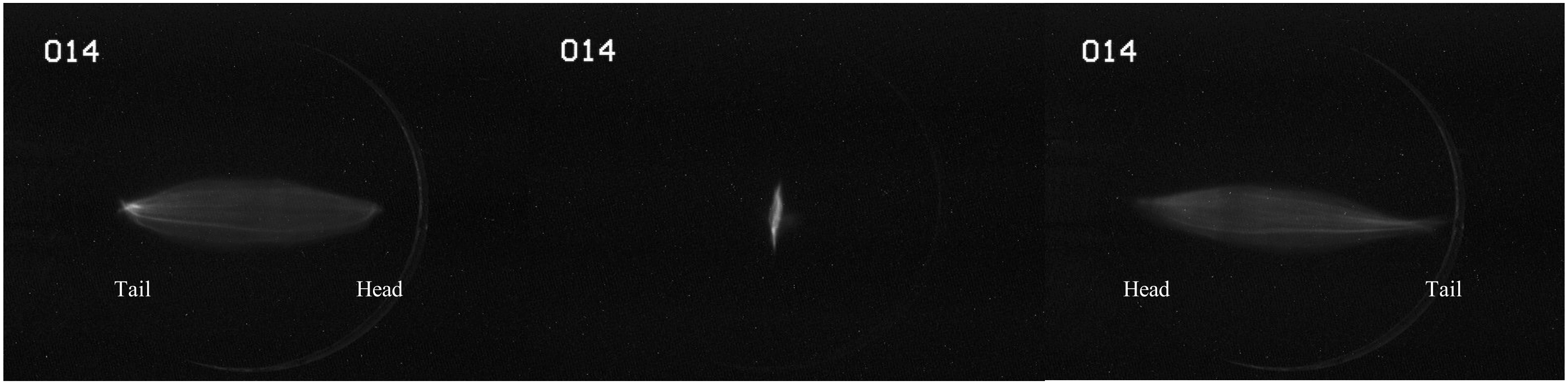
RF Zero Phase



Measure bunchlength by using linac to “streak” beam on profile monitor.

At DUVFEL, use tank3 to remove correlations from compression, tank 4 to produce chirp.

RF Zero Phase



Phase = -90 RF off Phase = +90

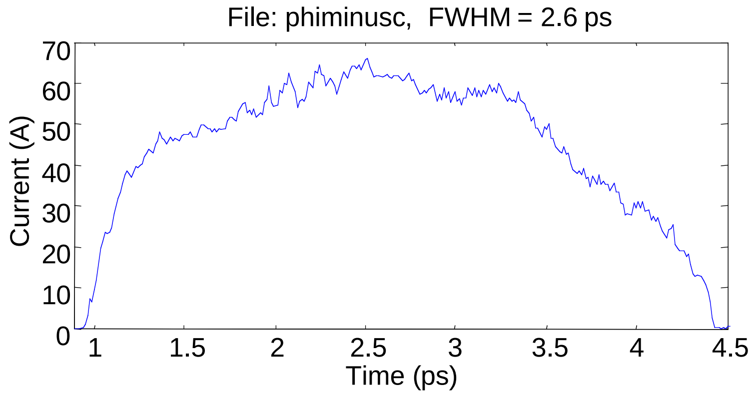
Charge	250 pC
Energy	75 MeV
Chicane	off
Tank 4	11 MeV

$$\sigma_t = \frac{E_0 \sigma_x}{\eta E_{rf} k_{rf} c} = \frac{(75\,\mathrm{MeV})(120\,\mathrm{um})}{(1.1\mathrm{m})(60\,\mathrm{MV})(60\,\mathrm{m}^{-1})c} = 8\,fs \text{ RMS time resolution}$$

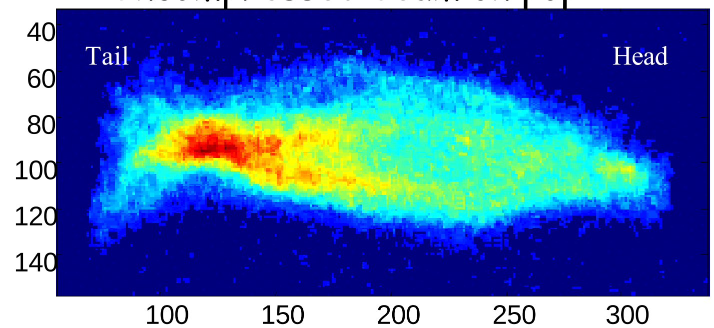
Much more information than bunch length is available.

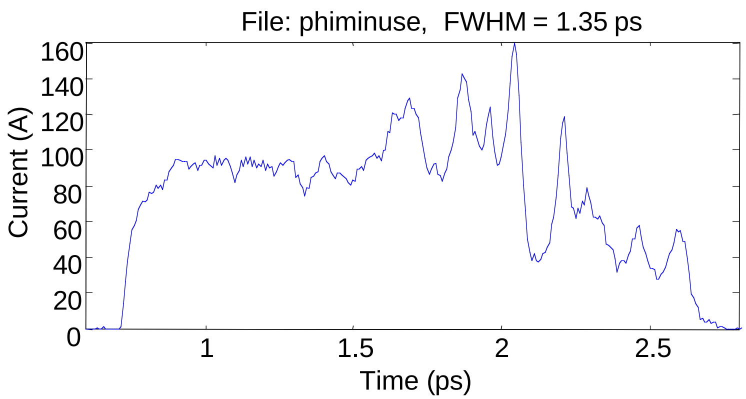
Find detailed time profiles and transverse slice dynamics

Microbunching at high compression

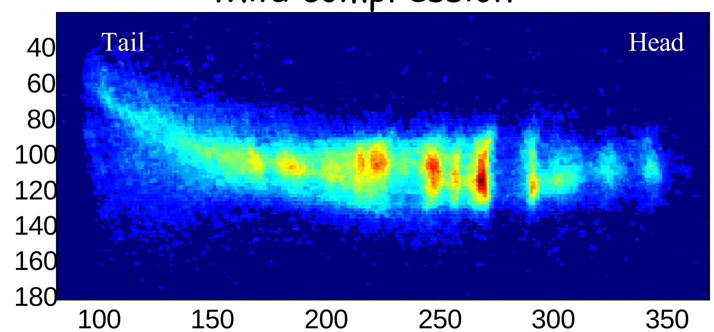


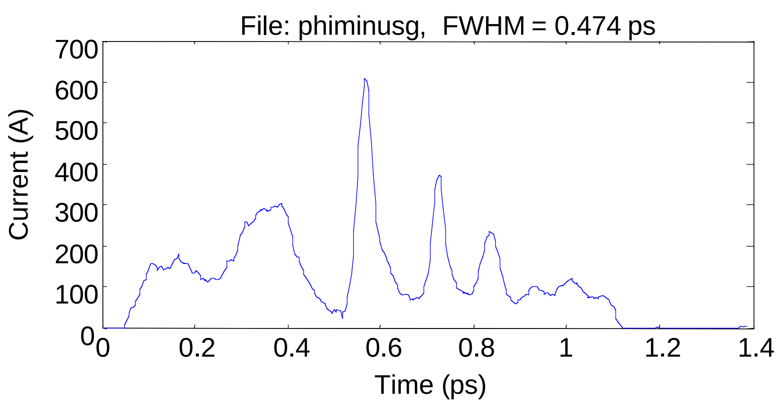
Uncompressed beam on pop14



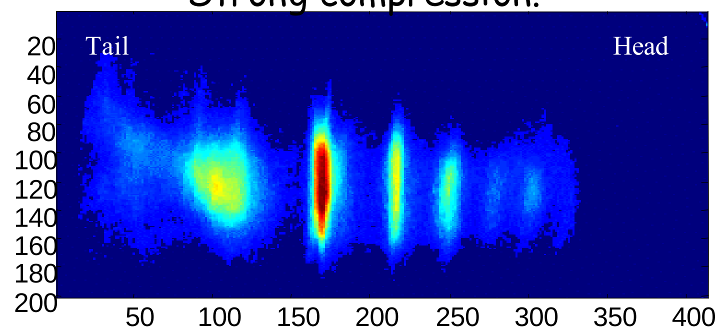


Mild compression





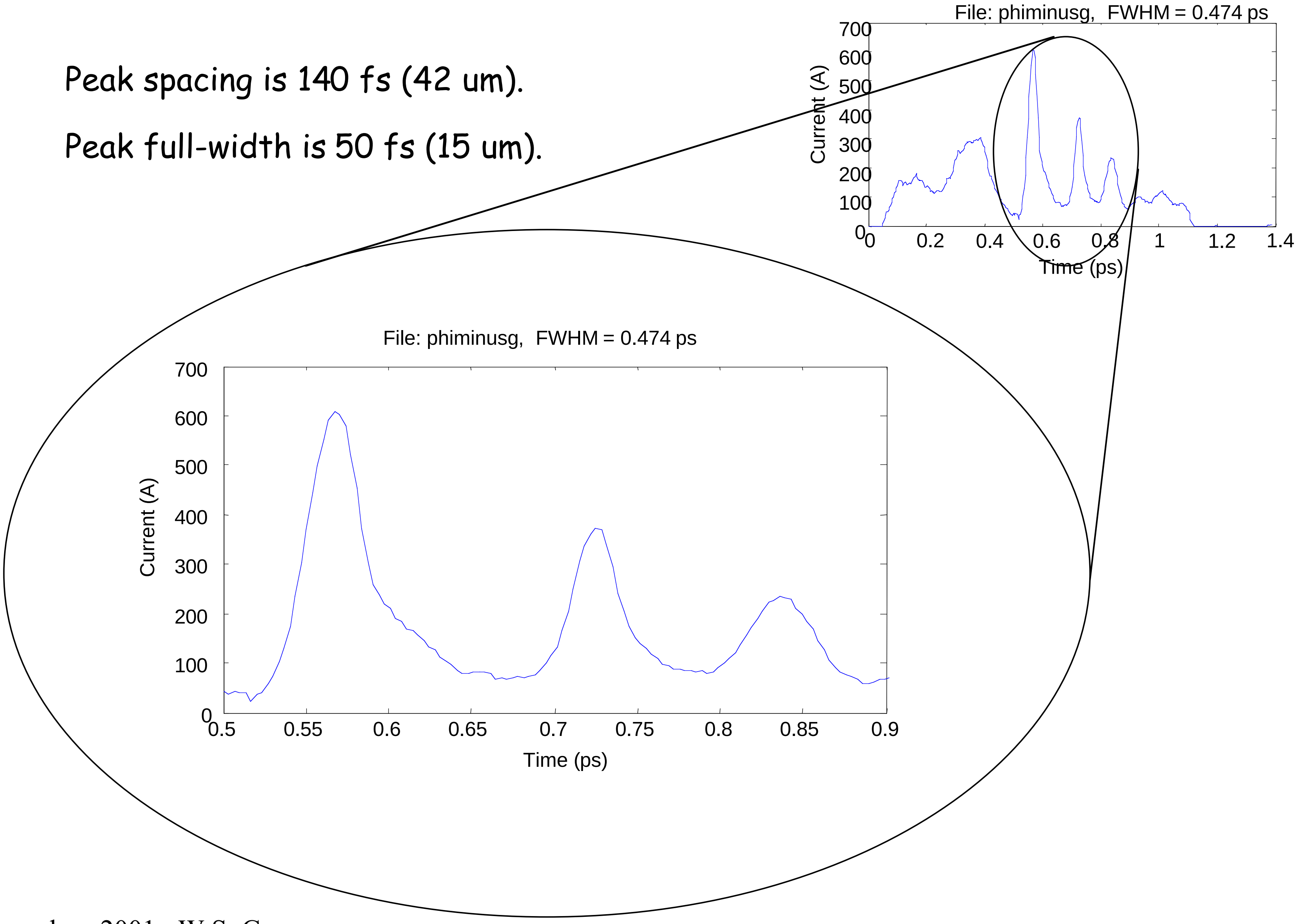
Strong compression.



50 femtosecond time resolution

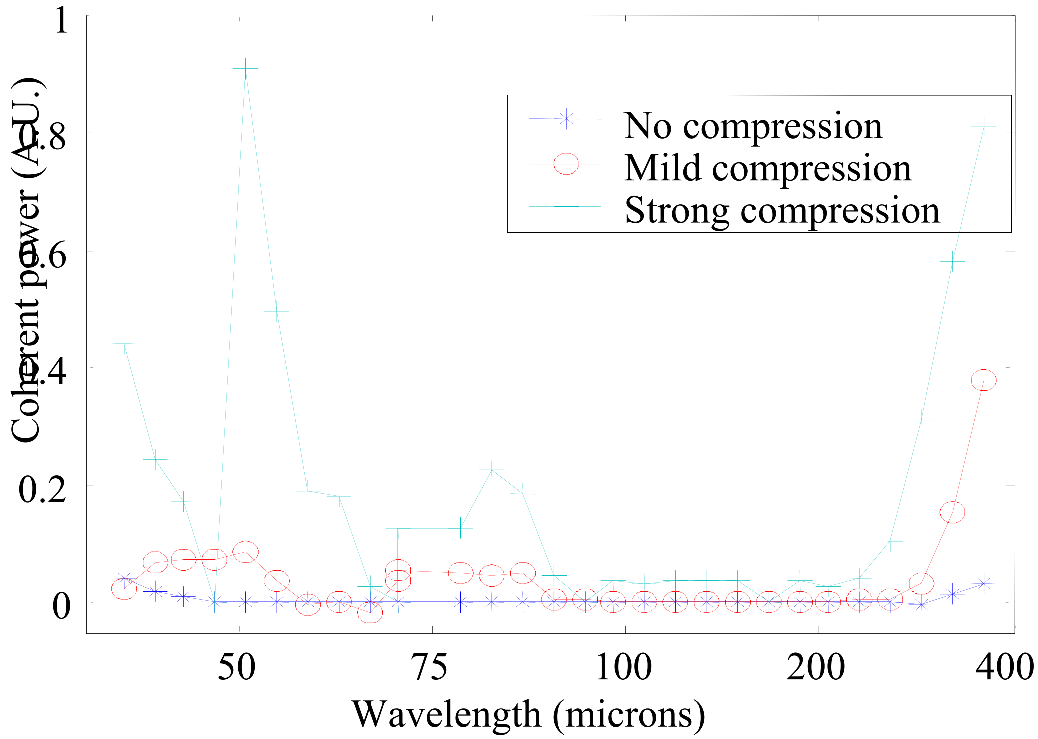
Peak spacing is 140 fs (42 um).

Peak full-width is 50 fs (15 um).



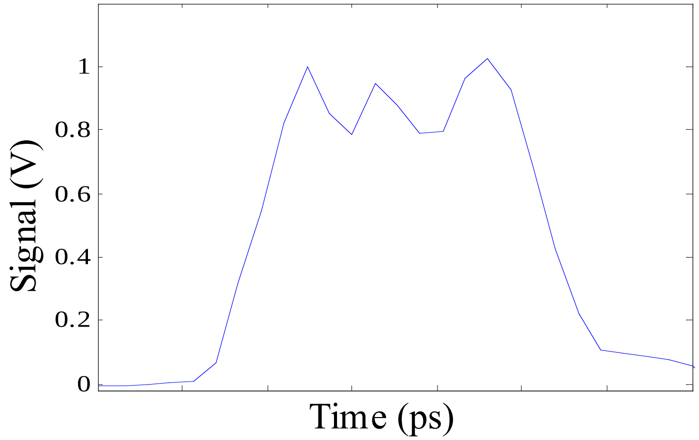
Infrared spectral measurement

Data and analysis from Larry Carr



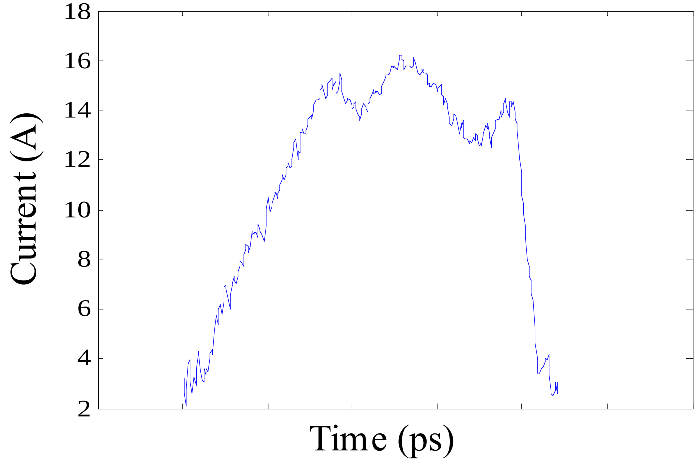
These spectra were recorded concurrently with the three RF zero-phasing time profiles on the previous slide.

Modulations on photoinjector drive laser may seed CSR microbunching.



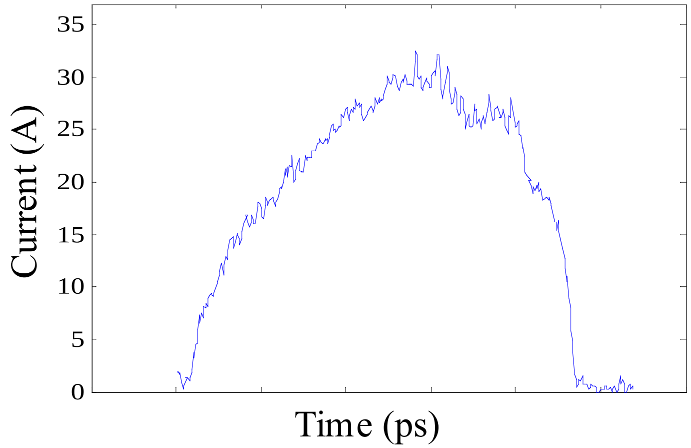
UV laser time profile

Resolution = 200 fs, RMS length = 0.97 ps



Uncompressed e-beam time profile (50 pC)

Resolution = 200 fs, RMS length = 1.05 ps.

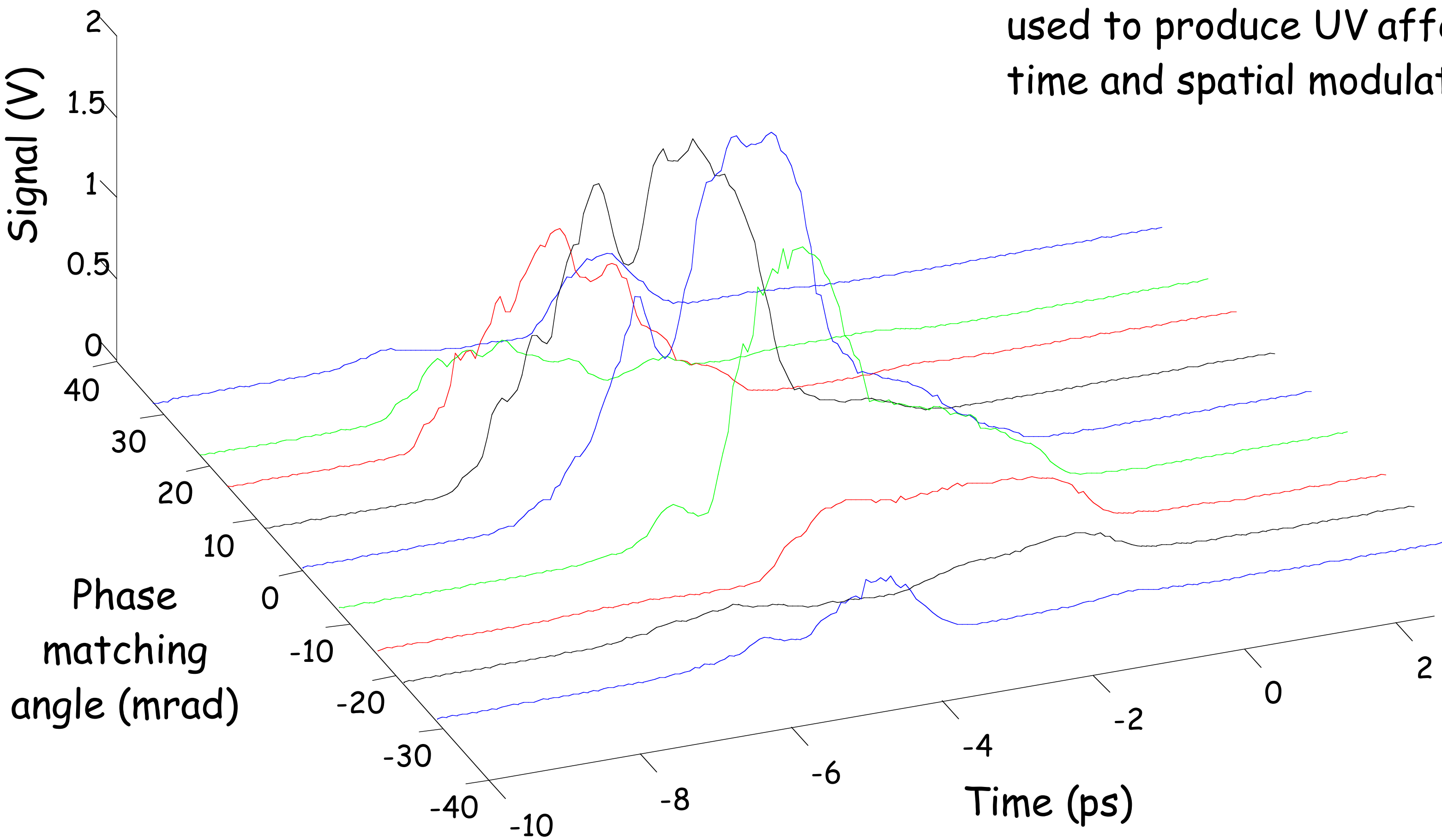


Uncompressed e-beam time profile (100 pC)

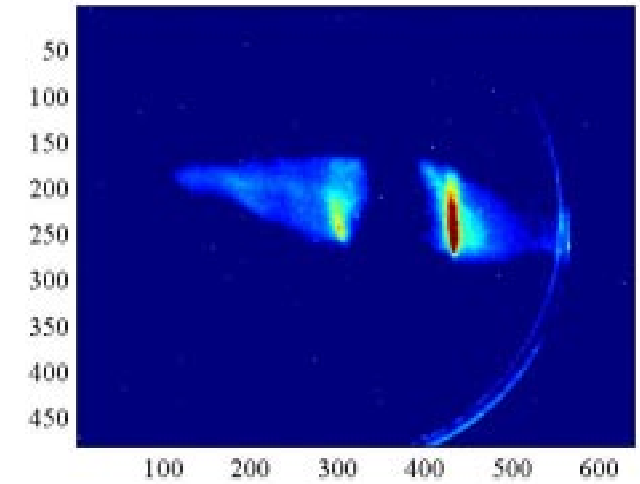
Resolution = 200 fs, RMS length = 1.13 ps.

Time modulations on UV laser pulse

Phase matching angle of harmonic generation crystals used to produce UV affects time and spatial modulations.

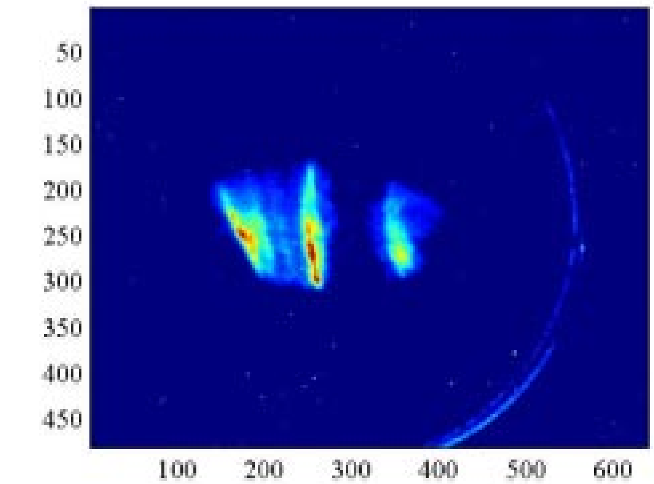


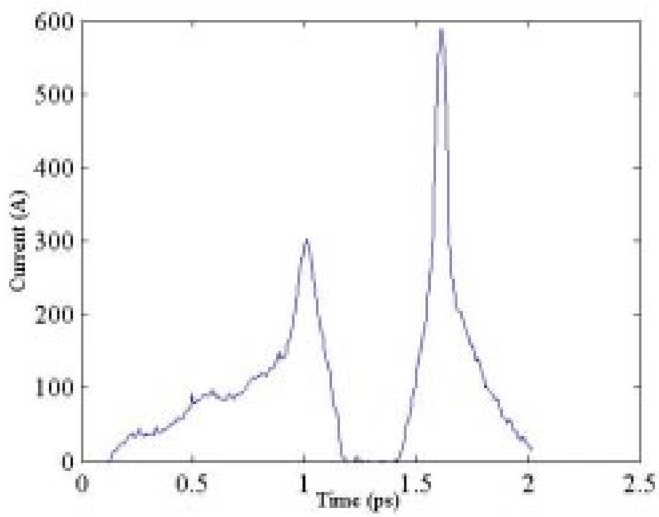
Recent Microbunching Measurement



Images of chirped, compressed ebeam from scintillator in dispersive section.

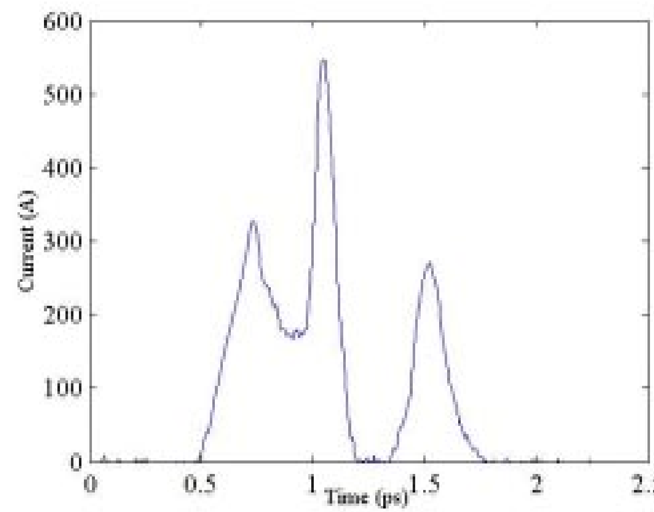
(RF zero phasing measurement)



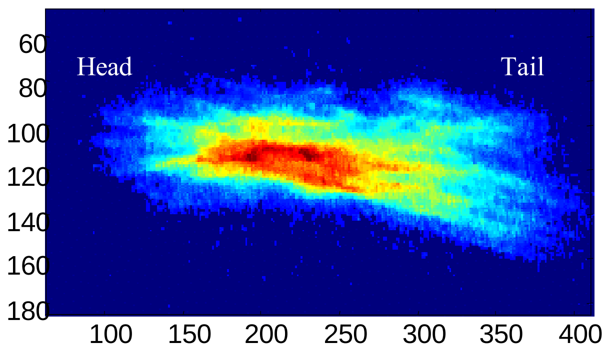


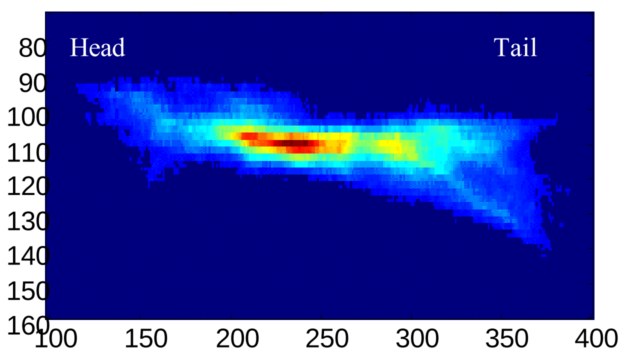
Projection of above images onto time axis.

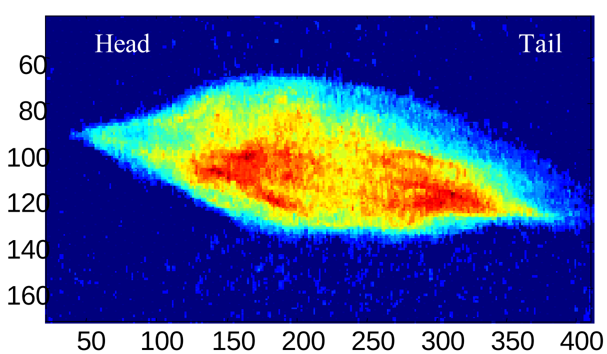
Compression phase is 26 degrees from crest…just before max compression.



Slice emittance measurement







Images on left

Beam distribution at 3 different quad settings.

Compare vertical size of center of beam with head and tail.

Plots on right

Alpha, beta, and emittance plotted as function of time slice.

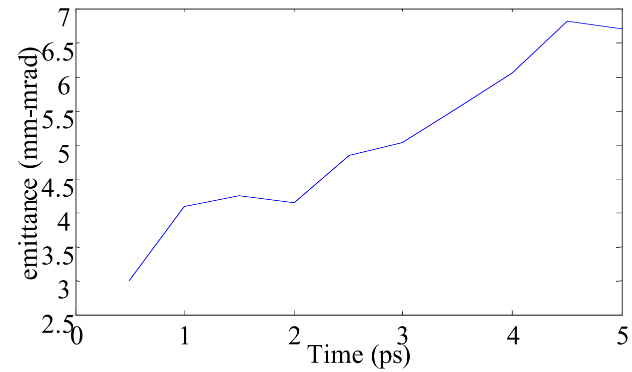
500 fs slice widths

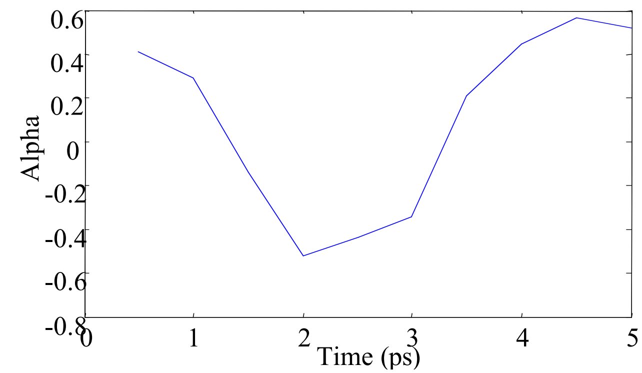
Projected beam parameters also measured to be

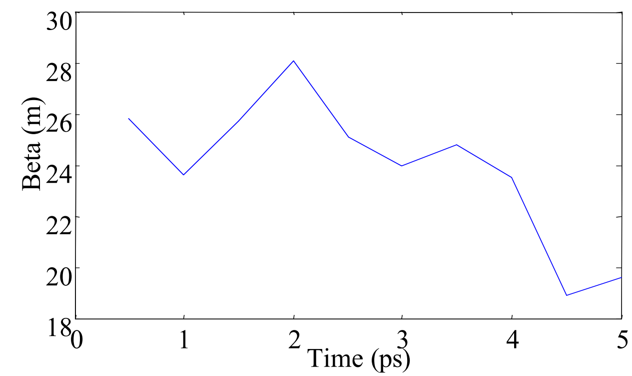
alpha = -0.3

beta = 22 m

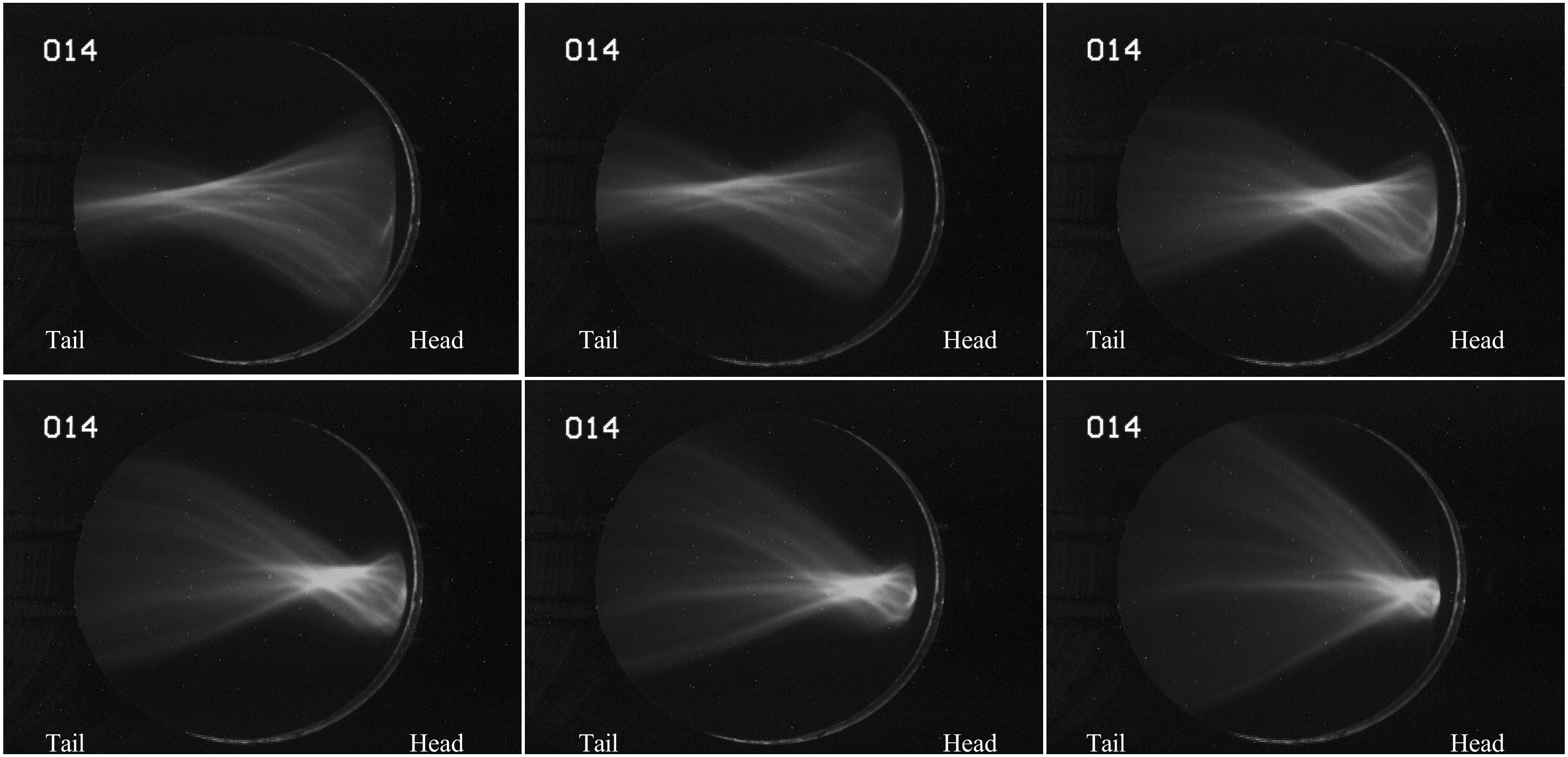
emittance = 5.3 mm-mrad







Laminar/cross-over trajectories



<u>Vertical dynamics</u>

Lattice is set to image end of Tank 2 to RF-zero phasing YAG.

Particles in tail of beam are diverging, and in head converging.

Head has higher current and so reaches waist at higher solenoid setting.

Increasing solenoid current

Summary

•Instrumentation demonstrates time resolution < 100 fs.

•Microbunching appears during compression…likely due to CSR instability seeded by photoinjector drive laser time modulations.

•Microbunched beam may be used as intense coherent IR source, or for novel accelerator tests.

•Combination of measurement techniques enables detailed study of transverse slice dynamics.